

Understanding Precipitation Changes in Iberia in Early Spring: Weather Typing and Storm-Tracking Approaches

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ABSTRACT

March monthly accumulated precipitation in the central and western regions of the Iberian Peninsula presents a clear continuous decline of 50% during the 1960–97 period. A finer analysis using daily data reveals that this trend is exactly confined to the month of March. However, this is merely the most visible aspect of a larger phenomenon over the North Atlantic/European sector. The European precipitation trends in March for the period 1960–2000 show a clear distribution of increasing precipitation in the northern regions (the British Isles and parts of Scandinavia) together with decreasing trends throughout the western Mediterranean Basin.

Relevant circulation changes over the North Atlantic and European sectors explain these precipitation trends. First, a regional Eulerian approach by means of a weather-type (WT) classification shows that the major rainfall contributors in March display significantly decreasing frequencies for the Iberian Peninsula, in contrast to the corresponding “wet” weather types for the U.K./Ireland sector, which display increasing frequencies. Within a larger context, a Lagrangian approach, based on the analysis of storm tracks over Europe and the North Atlantic region, reveals dramatic changes in the location of cyclones in the last four decades that coincide with the corresponding precipitation trends in Europe. The North Atlantic Oscillation is suggested to be the most important large-scale factor controlling both the circulation changes and the precipitation trends over the Euro–Atlantic area in March. Finally, the potential impact of reduced precipitation for rivers and water resources in the Iberian Peninsula is considered.

1. Introduction

The Mediterranean climate is under the influence of both tropical and midlatitude climate dynamics, being directly affected by continental and maritime air masses

with significant origin differences (Barry and Chorley 1998; Reale et al. 2001). The highly seasonal Mediterranean climate is controlled by the westerlies dominating the winter circulation and by the Azores anticyclone, which prevails in summer. In this region, most of the precipitation occurs during the winter half of the year. The peak of the winter season occurs between December and February (DJF), when the midlatitude cyclone belt has usually reached its southernmost position [e.g., (Her Majesty’s Stationery Office) HMSO

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1962).] During these months the synoptic lows and troughs, steered along the meanders of the polar front jet, are more likely to directly influence Mediterranean cyclogenesis and weather, with the highest impact over the northern coast (Trigo et al. 2000).

As a result of the influence of both the Atlantic Ocean and the Mediterranean Sea, the precipitation regime over the Iberian Peninsula is characterized by a strong seasonal behavior (Esteban-Parra et al. 1998; Trigo and DaCamara 2000). The central and western regions of Iberia are characterized by maximum rainfall records from November to February. However, eastern Iberia presents an absolute maximum in autumn and a secondary maximum in spring (Rodríguez-Puebla et al. 1998; Trigo and Palutikof 2001). Thus, Iberia as a whole presents the largest concentration of rainfall during the winter half of the year (from October to March). During this season, precipitation is mainly related to baroclinic synoptic-scale perturbations moving eastward from the Atlantic Ocean, although mesoscale convective systems are also responsible for high rainfall rates in the eastern half of the Iberian Peninsula (García-Herrera et al. 2005). In contrast, the scarce summer precipitation is mostly due to local factors and convective storms (Serrano et al. 1999b).

Besides the enhanced seasonal character, the Iberian Peninsula, as well as the whole Mediterranean region, is also characterized by a strong interannual variability of precipitation. As a consequence, very wet and dry years occur with some frequency, strongly affecting the hydrological cycle. This is particularly problematic since river flow and water resources are impacted, and this represents a major problem in the areas of increasing demands on water supply from domestic and agricultural sectors (Trigo et al. 2004b). Overall, the Mediterranean region, and the Iberian Peninsula in particular, are highly sensitive to variations in precipitation amount, a vulnerability that has produced intense public and political interest (Thornes 1998).

It is a well-known fact that Iberian monthly and seasonal winter precipitation can be explained in terms of a few large-scale modes of variability. The most prominent one is the North Atlantic Oscillation (NAO), which has been widely recognized to exert strong control on precipitation variability over the Iberian Peninsula (Rodríguez-Puebla et al. 1998; Trigo et al. 2004b; Goodess and Jones 2002). This influence also extends to parts of the European continent, showing the relevance of the NAO mode to the winter surface climate (R. M. Trigo et al. 2002). However, it should be stressed that other large-scale modes of atmospheric circulation, namely the eastern Atlantic (EA) and the Scandinavian pattern (SCAN) are also relevant to precipitation over

Europe (e.g., Qian et al. 2000) as well as for Iberia (e.g., Sáenz et al. 2001; Rodríguez-Puebla et al. 1998; Trigo and Palutikof 2001). Among other direct influences, the NAO pattern controls, to a large extent, the preferred location of storm track paths over the North Atlantic region (Osborn et al. 1999; R. M. Trigo et al. 2002). This is crucial for the Iberian precipitation regime, since transient low pressure systems with Atlantic origin constitute the main source of rainfall during the winter half of the year, as shown by studies relating precipitation and circulation patterns at the daily scale (Zhang et al. 1997; Corte-Real et al. 1998; Trigo and DaCamara 2000; Goodess and Jones 2002).

There are several studies indicating a general decline in winter precipitation, particularly in the northern Mediterranean Basin (Zhang et al. 1997; Amanatidis et al. 1993; Piervitali et al. 1997; Trigo and DaCamara 2000). These negative trends are likely to be associated with the decrease in storm frequency for that area (e.g., Trigo et al. 2000; Alpert et al. 2002; Xoplaki et al. 2004). Over the western Mediterranean sector the most prominent trend of precipitation occurs during early spring, particularly during the month of March. Using precipitation data until the early 1990s, some authors have characterized an intense decline of precipitation in March over Portugal (Corte-Real et al. 1998; Trigo and DaCamara 2000) and for the whole Iberian Peninsula (Serrano et al. 1999a). Moreover, this decline can be found not only over the last three or four decades (Corte-Real et al. 1998; Trigo and DaCamara 2000), but also at larger time scales for the entire twentieth century (Schoenwiese 1993; Serrano et al. 1999a). The concern about this precipitation decline is enhanced by the recent climate change scenarios developed for the European continent, which have identified the risk of increasing summer droughts in Europe, particularly in the south (Parry 2000). Moreover, climate change scenarios obtained with different GCMs reveal that there is a general agreement toward a significant decrease of precipitation for this region among most general circulation models (Houghton et al. 2001). It is essential, therefore, to understand the mechanisms that link changes in the general circulation of a warming global climate and those directly responsible for the bulk of Iberian rain events (Trigo and Palutikof 2001).

In contrast to Iberia, other western European regions have shown positive trends of March precipitation in recent decades. In particular, positive and significant trends have been detected for Ireland (Kiely et al. 1998; Hoppe and Kiely 1999) and Scotland (Smith 1995). This evidence supports the idea of a changing precipitation scenario in March for parts of the western European continent. We acknowledge that in recent years, a num-

ber of authors have looked at negative and positive precipitation trends for March in western Europe, however, to the best of our knowledge, none of them have addressed the following:

- 1) What is the actual length (weeks) affected by the negative trend over Iberia, that is, is this trend observed in late February or early April? And is this trend monotonic and fairly stable in time, or is it characterized by large jumps?
- 2) What is the spatial extent (and magnitude) of the regions in Europe presenting significant (negative or positive) trends for March? Are these trends triggered by regional synoptic-scale changes or induced by larger scale modes?

The widespread decline of March precipitation in Iberia, and the consistent negative precipitation trends predicted by most climate change scenarios, increase the concern about a possible future scenario with scarce water resources. It is within this context that the detected decrease of precipitation in March can be indicative of “things to come,” that is, lack of precipitation and water when it is most needed for spring plant growth as well as for human consumption during spring and summer seasons (Pereira et al. 2002). If the average of March precipitation is kept within the present range of values and summer droughts become the norm, it is not difficult to foresee increasing water resources problems, including those of a transnational nature between Portugal and Spain (Vlachos and Correia 1999).

Therefore, the main objectives of this paper are the following:

- 1) To characterize the decrease of precipitation in western and central Iberia during March, using both daily and monthly datasets. To put it into a larger context by analyzing the spatial extent of the (significant) precipitation trends throughout the European continent.
- 2) To analyze different physical mechanisms responsible for the decrease of precipitation in March. The role played by changes in cyclones affecting this region, using an Eulerian framework (weather types) and also a Lagrangian technique (objective storm tracks) will be assessed. Furthermore, the role played by the North Atlantic Oscillation and other major modes of atmospheric circulation will be explored.

In section 2 a brief summary of the data used in this research is presented, then, in section 3, a detailed characterization of the intense decrease of precipitation in March over the Iberian Peninsula is described. Section 4 presents the precipitation changes in Europe and the

corresponding changes in storm tracks. Finally, the discussion and main conclusions of results are presented in section 5.

2. Data

- 1) To analyze the precipitation over the Iberian Peninsula three different daily and monthly precipitation datasets were examined. Daily data series between 1941 and 1997 were obtained from both National Meteorological Institutes of Portugal (IM, 4 stations) and Spain (INM, 46 stations). The Portuguese stations had few missing data (less than 1% for each series) and no filling method was applied. Gaps in the Spanish stations time series were filled using the method described in Karl et al. (1995). Finally, to cover a few spatial gaps five additional precipitation series, made available by the European Climate Assessment (ECA) project (Klein et al. 2002), were used (Coimbra and Tavira, Portugal, and Malaga, Salamanca, and Zaragoza, Spain). The total number of stations with daily data was 55.
- 2) The daily weather-types (WTs) dataset is derived for the Iberian Peninsula, for the 1941–97 period, using an algorithm previously developed by Trigo and DaCamara (2000). The equivalent corresponding WTs classification for the U.K./Ireland sector is also used. These are objectively defined Lamb weather types (Jones et al. 1993), which can be downloaded from the Climate Research Unit (CRU) site.
- 3) The storm detection and tracking scheme is performed using 6-hourly geopotential height at 1000 hPa, available from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analyses (ERA 40) on a $1.125^\circ \times 1.125^\circ$ grid (Simmons 2001). The data cover a wide area (30° – 80° N and 60° W– 70° E), enclosing Europe and most of the North Atlantic sector, for the period 1958–2000.
- 4) The European precipitation trends between 1960 and 2000 are computed using the CRU high-resolution (0.5° latitude by 0.5° longitude) dataset of monthly precipitation (New et al. 1999) derived from a worldwide network of observations, particularly dense over Europe.

3. Regional trends in Iberia

a. Precipitation changes in Iberia

Trends of monthly accumulated precipitation for the month of March are computed for the available Iberian stations between 1941 and 1997 (Fig. 1a). Their sta-

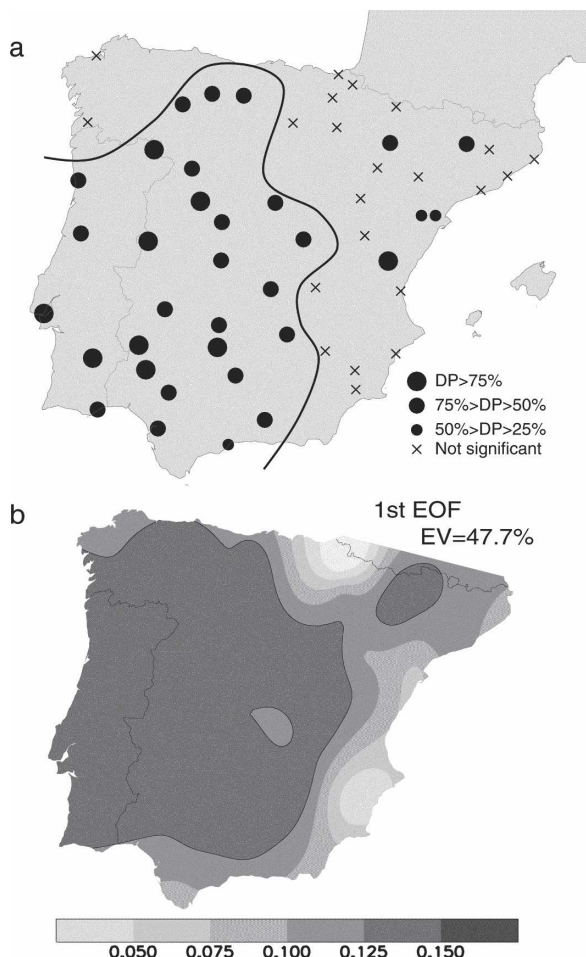


FIG. 1. (a) Decreasing precipitation (DP) trends in March for the period 1941–97. The different sizes of black dots depict the relative change in precipitation for the complete period after fitting March time series to a linear model. The cross signs correspond to nonsignificant or positive trends, while the dots represent stations with declining precipitation at less than the 10% level (Mann–Kendall test). (b) The spatial pattern for the first EOF obtained with a PCA analysis applied to March precipitation during the same period.

tistical significance is evaluated through the Mann–Kendall nonparametric test; any trend is considered to be significant at $p < 0.1$. To assess the relative amount of precipitation decrease, the precipitation series were also fitted to a least squares linear regression model, which is the simplest model for an unknown trend and has also been used in recent works dealing with precipitation trends over Iberia (Goodess and Jones 2002; Trigo and DaCamara 2000; Serrano et al. 1999a). The most important result is the appearance of a large homogeneous region (28 contiguous stations) revealing highly significant decreases of March precipitation and covering most of the central and western

Iberia (Fig. 1a). These trends reflect changes of more than 50% in relative precipitation since 1941 in most of the stations showing significant trends, in agreement with previous works dealing with monthly precipitation for March over Portugal (Zhang et al. 1997; Trigo and DaCamara 2000) and for the whole Iberia (Serrano et al. 1999a). It should be emphasized that most of eastern and northern stations of Iberia, however, do not show significant trends (Fig. 1a).

To detect a spatial link between all the stations presenting significant negative trends, an S-mode principal component analysis (PCA) is computed for the Iberian March precipitation, taking into account the whole period available (1941–97) and using the correlation matrix. The spatial pattern obtained for the first empirical orthogonal function (EOF) is almost identical for the nondetrended March precipitation field (Fig. 1b) and for the corresponding detrended first EOF (not shown). The explained variance is similar, accounting for 47.7% (46.2%) of the total variance for the nondetrended (detrended) data. Moreover, the region depicted by the first EOF component coincides very well with the region of negative trends (Fig. 1b). The Pearson correlation coefficient between the corresponding first PC and the precipitation average over stations with significant decrease is higher for the nondetrended data ($R = 0.94$) than for the detrended ($R = 0.80$). The region depicted also coincides with the first EOF obtained over Iberia for analysis performed at the annual (Rodríguez-Puebla et al. 1998), winter (Zorita et al. 1992) and monthly (Serrano et al. 1999b) scales.

Changes of Iberian March precipitation should be visible when we compare climatological normals computed for the latest two consecutive 30-yr periods available (e.g., 1941–70 and 1971–2000). This analysis should be performed for the entire year in order to assess each month individually and also the combined effect of all changes on seasonal and yearly averages. Unfortunately, we only have data until 1997, thus, we had to restrict the second climatological normal to the 1971–97 shorter period. We believe this small change in length (10%) yields minor implications on our results. Averages in space and time were computed for each month over the contiguous region (see Fig. 1a), with stations presenting significant negative trends in March, for both periods of 1941–70 and 1971–97. Absolute (millimeter) and relative (percentage) precipitation changes were computed, showing the monthly differences in Fig. 2a. It is clear that March presents the highest variation in precipitation of all months, with an absolute decrease of roughly 40 mm, representing a decline of nearly 50% during the studied period. The variations in the remaining months are less intense and small in-

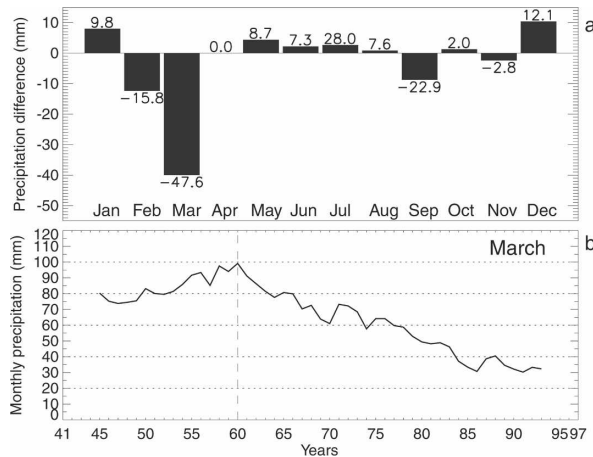


FIG. 2. (a) Absolute precipitation change (mm) between the 1941–70 and the 1971–97 normal periods. The corresponding relative change (%) is also indicated over (or below) each column. (b) The 9-yr moving average of spatially averaged precipitation in March (28 stations with significant decrease). The vertical dashed line indicates the location of the changing point for the trend.

creases in January and December are offset by corresponding decreases in February and September. Overall, the annual decrease of averaged precipitation in this region is related with the strong decrease observed in March (Miranda et al. 2002). The inclusion of this month in winter or in spring seasonal averages will impact dramatically when computing trends for those seasons. Despite the strong negative trends found in Fig. 1a, it is important to accurately pinpoint the initial moment of this dramatic descend. After applying the same spatial average as in Fig. 2a for the monthly precipitation in March to the complete period (1941–97), the first years of the 1960s emerge as the changing point (Fig. 2b).

We decided to study the width of this precipitation trend using the entire Julian year. This should allow an objective assessment of the temporal window affected by this strong decrease. In particular, it would be useful to understand if the decrease starts and/or ends within the month of March or if, on the contrary, starts before 1 March and ends well into April. For this purpose, a spatial daily average, including all 28 stations identified within the homogeneous region previously defined, was computed for each calendar day. Then, taking into account the large variability of precipitation at the daily scale, a moving average window of 15 days was applied to the entire spatially averaged time series. Finally, we computed 10-yr moving averages between 1952 and 1997, but for the sake of simplicity, we restrict our presentation (Fig. 3) to the first (1952–61) and last (1988–97) decades. The first decade is chosen for being representative of the precipitation values just before the

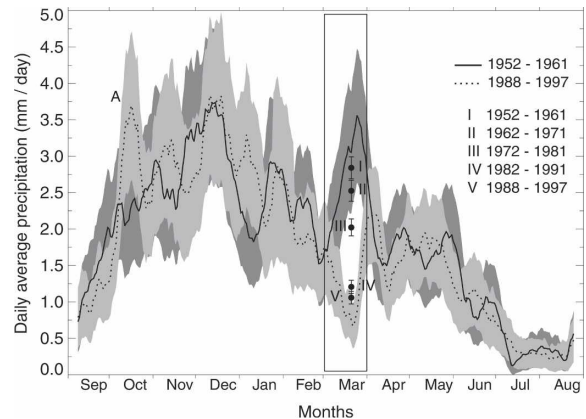


FIG. 3. Daily average precipitation and corresponding error bars during the whole Julian year for the 1952–61 (solid line and dark gray shadow) and 1988–97 (dotted line and light gray shadow) decades; curves and error bars are smoothed through the application of a 15-day moving average. Black dots depict the average precipitation in March for the five 10-yr periods displayed in the figure. The error bars for both the curves and the dots display the $2\sigma/\sqrt{N}$ level, N being the sample size. The rectangle indicates the beginning and end of March.

decreasing trend started in the early 1960s (Fig. 2b). Smoothed error bars for the 1952–61 (dark shading) and 1988–97 (light shading) decades were also plotted. It should be stressed that the only time of the hydrological year presenting nonoverlapping error bands is located precisely in the middle of March, confirming the significant nature of this decline. Figure 3 also shows a considerable number of interesting features, namely:

- 1) The most impressive changes of decadal averages between the first and last periods are indeed confined to the month of March. It is worth noticing that both time series present very similar averaged values of daily precipitation for the early and final days of March;
- 2) This decrease in March presents clear monotonic nature since the 1950s. This fact is highlighted by the five numbered black dots that correspond to five consecutive decades. The ratio of average precipitation in March, between the first and last decades represented, is almost 3 to 1.
- 3) The wet period from October to March presents high variability at the decadal scale. In particular, it is worth noticing the upward trend for October (Fig. 3, A), although some other changes are partially offset because they are split between different months (e.g., December and January).

b. The circulation weather-type approach

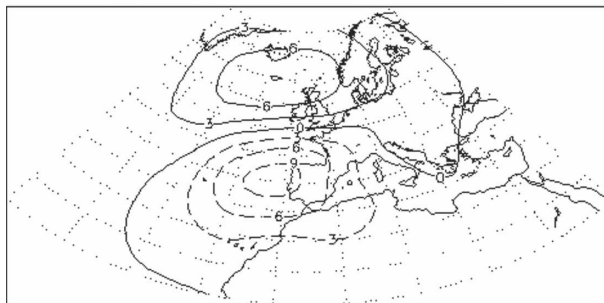
Using a previously developed WT classification scheme for Iberia (Trigo and DaCamara 2000), we have

computed the relative contribution to precipitation of each type in every station on a month-by-month scale during the 1941–97 period. It should be emphasized that this classification has been broadly used in recent studies of variability and trends of Iberian precipitation (Spellman 2000; Trigo and DaCamara 2000; Goodess and Jones 2002), and also for the construction of climate change scenarios (Goodess and Palutikof 1998; Miranda et al. 2002) and even linking storm lightning activity to atmospheric circulation (Tomás et al. 2004). Here, the approach firstly proposed by Trigo and DaCamara (2000) is used, based on the corresponding objective classification defined for the British Isles (Jenkinson and Collison 1977; Jones et al. 1993). In this scheme, 26 types are assigned, which include 8 purely directional types dominated by strong straight flows (within 45° sectors), 2 other WT types dominated by the strength of vorticity (cyclonic and anticyclonic types), and then 8×2 hybrid types. To obtain a more practical analysis scheme, the WT types are regrouped by including any of the hybrid types into the corresponding pure directional and cyclonic/anticyclonic types with a weight of 0.5 (Trigo and DaCamara 2000).

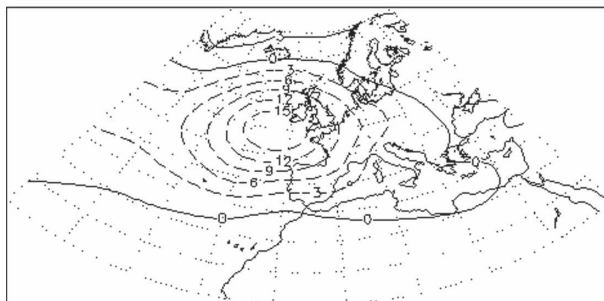
The WT types contributing to the highest fraction of winter (DJF) precipitation over Iberia (Trigo and DaCamara 2000; Miranda et al. 2002; Goodess and Jones 2002) are those considered as cyclonic (C) and those with a predominant directional flow from the Atlantic [west (W), southwest (SW), or northwest (NW)]. These circulation–rainfall relationships appear to be very consistent during the second half of the twentieth century (Goodess and Jones 2002). To assure that the circulation patterns displayed by the WT types in March remain unchanged compared to winter, the composite maps of the March sea level pressure (SLP) anomaly field for the most relevant “wet” WT types in winter (C, W, and SW) are presented in Fig. 4. The spatial location of the positive and negative anomaly patterns is in fact almost identical to those obtained for winter (Trigo and DaCamara 2000), albeit the intensity of the anomalies displayed by the C type, which are slightly less intense for the March configuration.

The analysis of the WT types that mostly affect those stations with strong decreasing precipitation trends in March reveals that rainfall is always dominated by types C and W, although SW or NW types can also play a significant role, providing further evidence that the air masses with Atlantic origin account for the bulk of March precipitation. Despite accounting for only 28.3% of total days in the period 1941–97, the combined percentage of accumulated precipitation in March for the C, W, and SW WT types ranges from 53.4% to 76.6% among these stations (Fig. 5). Rainfall in the remaining stations

(a)



(b)



(c)

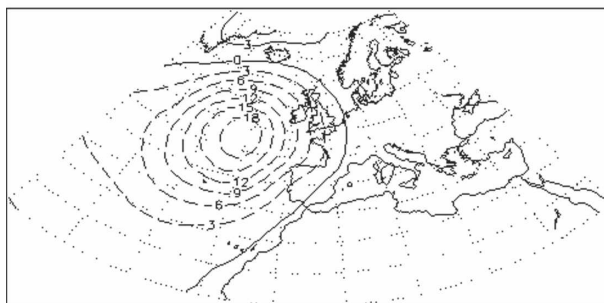


FIG. 4. Composite maps of anomaly SLP fields for (top) C, (middle) W, and (bottom) SW (i.e., the three “wet” WT types in March during the period 1941–97). Dashed (solid) lines display negative (positive) anomalies.

(without significant precipitation trends, Fig. 1a) is mostly associated with circulation WT types bringing Mediterranean flow. As expected, the frequency of such WT types in March does not present significant changes during the last four decades (not shown). Along with the negative trends in the frequency of those wet WT types (Table 1), their respective contribution to station rainfall also reveals significant declines, particularly for W and C, and, to a lesser extent, for SW circulation types (Fig. 6). To determine the robustness of our results, a Monte Carlo test (randomizing 1000 times the WT types accumulated frequency series for March) has also been performed. Results confirm the strong trends pre-

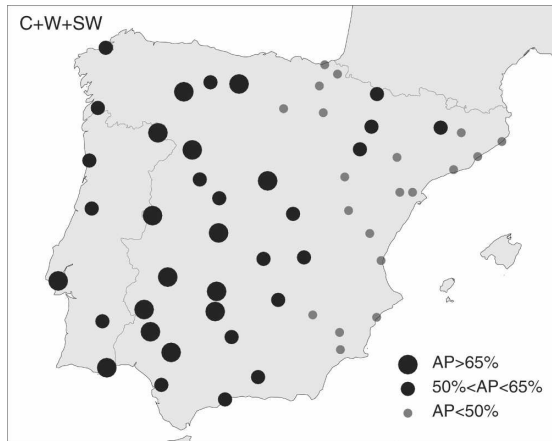


FIG. 5. Percentage of accumulated precipitation (AP) in March for the combination of weather types C, W, and SW during the period 1941–97.

viously found by applying the Mann–Kendall test (Table 1).

4. Climatic and circulation changes over the Atlantic

a. Changes of precipitation in Europe

There is evidence of increasing precipitation in northern Europe since the 1970s (Smith 1995; Schoenwiese 1993). Other researches prove the existence of increasing annual average and spring precipitation over northern Norway (Hanssen-Bauer and Forland 1998). Significant negative trends have also been detected as far south as the Canary Islands (García-Herrera et al. 2003). These suggest that the Iberian trends might be associated to a wider-scale phenomenon. Nevertheless, within the present scope, the most important results correspond to those works that have found significant

TABLE 1. (first row of numbers) Sign of trends of accumulated frequencies for March for the WTs C, W, SW, and A; the associated confidence level is also given in parentheses after applying a Mann–Kendall test. (second row) Confidence level resulting from the Monte Carlo test (1000 elements sample). (last row) Pearson correlation coefficient between March average frequency of each “wet” WT and the March NAO index; values in bold are statistically significant at the 5% level.

	C	W	SW	A
Iberia	−(0.985) 0.992	−(0.960) 0.980	−(0.940) 0.972	+(0.987) 0.993
	−0.58	−0.36	−0.23	+0.71
United Kingdom	+(0.827) 0.904 −0.17	+(0.929) 0.958 +0.66	+(0.934) 0.982 +0.68	−(0.993) 0.995 −0.19

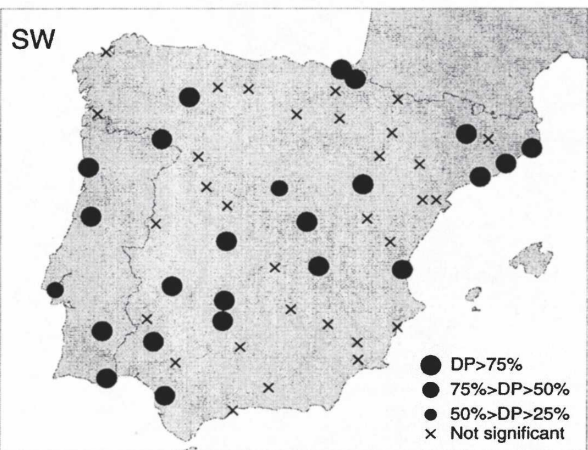
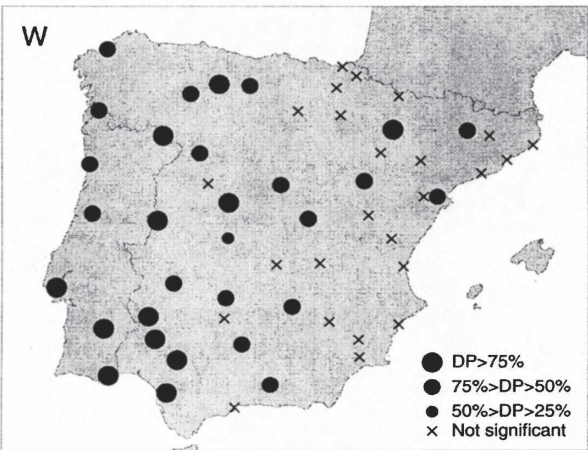
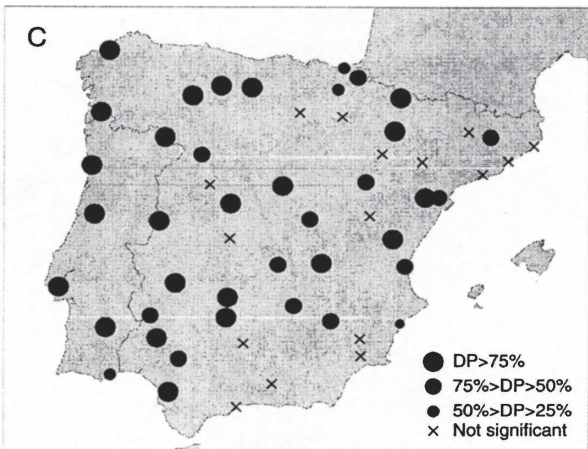


FIG. 6. Same as in Fig. 1a, but for precipitation that occurred for WTs (top) C, (middle) W, and (bottom) SW in March during the period 1941–97.

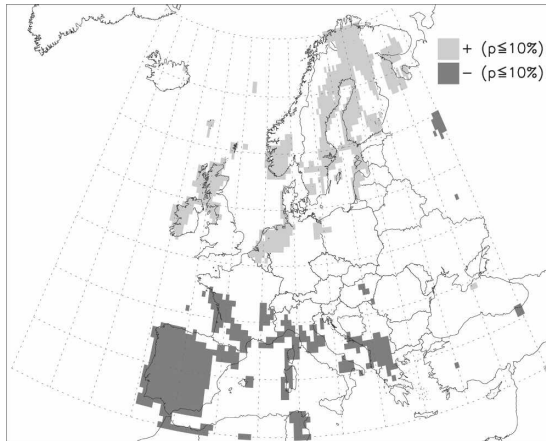


FIG. 7. Significance (%) of precipitation trends in March over Europe for the period 1960–2000, computed from the CRU monthly precipitation dataset. The trends are assessed using the Mann–Kendall test; only values significant at less than 10% are shown. Dark (light) gray cells correspond to negative (positive) tendencies.

positive trends of March precipitation for Ireland (Kiely et al. 1998; Hoppe and Kiely 1999) and Scotland (Smith 1995). It is natural to suggest that these changes may be related to those detected for southern Europe, supporting the idea of a changing precipitation scenario in March for a large sector of the western European continent. To examine this point we have computed trends for March, using the high-resolution precipitation data from CRU (New et al. 1999). Results are shown in Fig. 7, where the most striking result is the appearance of two contrasting areas displaying positive (northern Europe) and negative trends (southern Europe). For the sake of simplicity, results are only displayed when the corresponding precipitation trends (positive or negative) are significant at least at 10%, although large areas of significant trends at 2% were also detected. As expected, the (western) Mediterranean Basin is affected by the largest continuous negative trend. In particular, the Iberian Peninsula presents a large and homogeneous region affected by such changes in March, perfectly compatible with the pattern previously shown (Fig. 1a). On the contrary, the northern European territory is affected by significant positive trends, which extend from Ireland and Scotland to the Scandinavian Peninsula.

For the U.K. sector it is relatively easy to assess the importance of atmospheric circulation changes, as this is probably the region in the world with the longest synoptic classification scheme, the automated version of the Lamb WT for the U.K./Ireland sector. In this scheme, 26 plus an unclassified WT are assigned, but to produce a realistic comparison between both sets of

WTs (Iberian Peninsula and United Kingdom/Ireland), the number of WT in Jenkinson and Collison (1977) is reduced by including any of the hybrid types into the corresponding pure directional and cyclonic/anticyclonic types with a weight of 0.5, a procedure initially proposed by Jones et al. (1993). Results reveal significant decreases in dominant dry WT, that is, anticyclone and increases of wet WTs C (not significant), W, and SW, both significant at 10%, exactly the opposite result found for the Iberian Peninsula (Figs. 8a,b and Table 1).

b. The role of storm tracks

In recent years several objective methodologies have been developed to track paths of individual storms (Serreze et al. 1997; Blender 1997; Trigo et al. 1999). Here, the detection and tracking of North Atlantic cyclones is based on the algorithm first developed for the Mediterranean region by I. F. Trigo et al. (1999, 2002) and recently adapted to the entire North Atlantic area (Trigo et al. 2004a). Cyclones are identified as minima

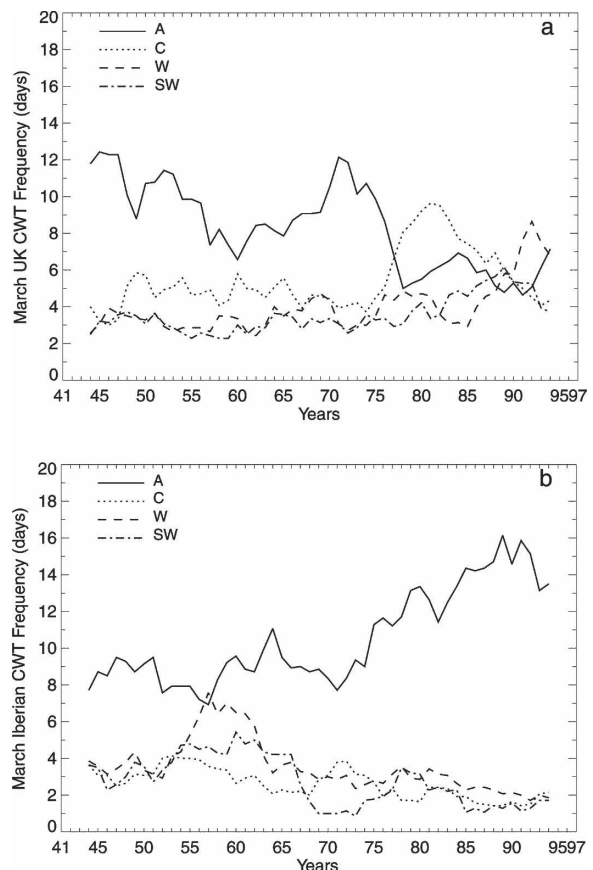


FIG. 8. Absolute frequency (moving average of 7 yr) of C, W, SW, and A WTs in March for (a) the U.K./Ireland sector and (b) the Iberian Peninsula.

in geopotential height fields at 1000 hPa, fulfilling a set of conditions regarding the central pressure and the geopotential gradient. The tracking is based on a nearest neighbor search in consecutive charts, assuming that the speed of individual storms is less than 50 km h^{-1} in the westward direction, and 110 km h^{-1} in any other. Further details on the cyclone detecting and tracking methodology may be found in I. F. Trigo et al. (1999, 2002), Trigo et al. (2004a), and Trigo (2005). For the purpose of this study, only lows lasting a minimum of 24 h and presenting minimum pressure values below 1010 hPa throughout their life cycle were considered.

Long-term averages and trends were computed at both monthly and seasonal scales for the period 1960–2000; however, taking into account the focus of this paper, we restricted the presentation of results to the average number of cyclones detected in March (Fig. 9a) and the respective decadal trends (percentage relative to the mean over the study period; Fig. 9b). The negative trend extending from the Azores archipelago, in the mid-Atlantic Ocean, to the west of Iberia is significant at least at 10%. The average decline per decade reaches values over 20% (of the mean cyclone count) at the northwest of Iberia, representing a decrease of over 60% of cyclonic centers between the first and last decades on record (relative to the first decade). On the contrary, the area between Scotland, Iceland, and Scandinavia reveals a strong increase (significant at 10%) of more than $15\% \text{ decade}^{-1}$ at its maximum (relative to the period's average), which corresponds to an increment of roughly 50% between the first and last decades. It is important to keep in mind that this type of algorithm identifies and follows cyclone centers, and thus the anomalies described (Fig. 9b) also correspond to densities of storm centers. Therefore, their associated impact on precipitation extends to the south of each main maximum/minimum shown, accompanying the main fronts associated with the synoptic systems tracked by the algorithm. A more complete analysis of decadal trends of winter cyclone counts for the Euro-Atlantic sector may be found in Trigo (2005).

The combined analysis of cyclone trends and large-scale precipitation over land gives a very useful and complementary perspective to the main issue under analysis in this work. In particular we can now state the following:

- 1) That negative trends in densities of cyclones centers have appeared not only near the Iberian Peninsula but also extend from northern Azores to Iberia. On the other side, equally significant (positive) trends dominate the synoptic picture over the North Sea.
- 2) These changes in the location of cyclones are obvi-

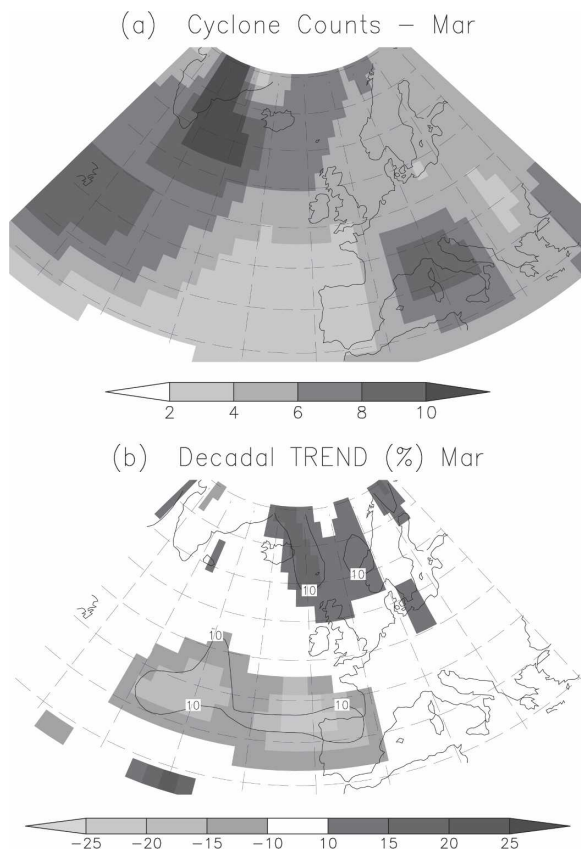


FIG. 9. (a) March climatology of cyclone counts, and (b) decadal trends (% relative to the mean over the study period) of the average number of cyclones detected in March; the solid line indicates the grid cells with significant trends at least at the 10% level. Both graphics were computed on cell boxes with 9° latitude by 9° longitude for the period 1960–2000.

ously related with contemporaneous changes in precipitation averages for those areas immediately under their influence (Fig. 7). Moreover, they are in agreement with the time series of WTs for both Iberia and the British Isles (Fig. 8).

c. The regional role of the North Atlantic Oscillation

The most important large-scale atmospheric mode controlling climate in the North Atlantic region during winter is the NAO, as has been proved by several studies (Hurrell 1995, 1996; Pozo-Vázquez et al. 2001). It is now accepted that the NAO index has a major impact on western Europe precipitation, particularly over the western Mediterranean Basin (Hurrell 1995; Qian et al. 2000; R. M. Trigo et al. 2002). This control exerted by the NAO on the precipitation field is related to corresponding changes in the associated activity of North Atlantic storm tracks (Serreze et al. 1997; Osborn et al. 1999; Ulbrich and Christoph 1999; Goodess and Jones

2002; R. M. Trigo et al. 2002). Nevertheless, one should bear in mind that the precipitation–NAO relation over the Iberian Peninsula is a nonstationary one (Goodess and Jones 2002; Trigo et al. 2004b), presenting higher correlation coefficient values during the 1960s and 1970s in the spring and during the 1980s and 1990s for winter.

The Pearson correlation coefficient between the spatially averaged precipitation series for the homogeneous region of the Iberian Peninsula previously described (Fig. 2b) and the normalized NAO index (Jones et al. 1997) in the period 1960–97 is -0.60 , statistically significant at less than 1%. This means that the NAO is responsible of 36% of the precipitation variance in March. Moreover, the spatial distribution of the correlation coefficient values below -0.5 over the Iberian Peninsula (Fig. 10) is highly coincident with those regions described by the first EOF and the region affected by the downward precipitation trends (Fig. 1). In addition to this, the NAO index in March also presents an upward trend (statistically significant at 2%), in contrast with the downward trend of precipitation in Iberia. If we remove the trend to both NAO and precipitation in March, then the correlation drops to -0.48 , a value that is still statistically significant at less than 1%, but considerably lower than the nondetrended value.

5. Discussion and conclusions

In this work the dramatic decrease of precipitation in March over the Iberian Peninsula has been analyzed and characterized. Further details show this decline in a wider context of changes occurring throughout the European continent. Robustness of results (trends, correlation coefficient, etc.) was assured though the use of appropriate statistical tests, therefore guarantying the highlight of those regions that present statistically significant levels.

Our initial efforts focused on the Iberian Peninsula, particularly on the region most affected by significant changes, which is confined to the central and western sectors of the peninsula. The location and spatial extension of this region is fairly coincident with the pattern obtained for the first EOF of precipitation for March. We have used daily precipitation data to perform a submonthly analysis in order to show that the significant trend does not start in mid-February neither does it end well into April. In fact, it is roughly confined between days 60 and 90 of the Julian calendar (i.e., to the month of March). Moreover, it was shown that a large and monotonic change of about 50% (40 mm) has occurred for the last four decades, starting in the early 1960s.

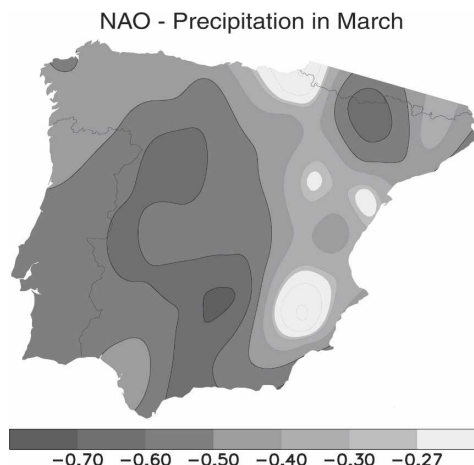


FIG. 10. Pearson's correlation coefficient between normalized accumulated precipitation in March and normalized NAO index during the period 1960–97. The shaded contours are for values lower than -0.27 and are statistically significant at less than the 5% level.

In the search for plausible physical mechanisms responsible for this trend, we first explore an objective WT classification technique that has been used frequently in recent years (Trigo and DaCamara 2000; Tomás et al. 2004). In this scheme three WTs account for most of the precipitation in March (between 50% and 75%) with only 28% of the days being classified as belonging to one of these types. Naturally, these “wet” WTs (e.g., C, W, and SW) display frequencies for the month of March that are significantly decreasing, accompanied by an equally increment of the dry anticyclonic type (A). This proves that low pressure systems and their associated fronts have become less frequent in March over the Iberian Peninsula when compared with four decades ago.

However, a number of different clues such as the high correlation with the NAO pattern and the appearance of significant trends in northern Europe have highlighted the hypothesis that what we have been observing in March over Iberia does not constitute an isolated phenomenon. This can be better assessed through the computation of storm track frequency trends (Trigo et al. 2004a) for the month of March, over a large window covering the North Atlantic and European sectors. The results reveal strong significant decline of cyclones centers from the Azores to Iberia. On the other side, significant positive trends are found over the northern Atlantic (between Greenland and Scandinavia). Naturally, these changes are related to the positive precipitation trends found for March over northern Europe, namely, the northern United Kingdom and parts of the Scandinavian Peninsula. The coincidence of

the regions affected with upward and downward trends in Europe and the correspondent location of cyclone trends allow us to conclude that precipitation changes have been largely driven by changes in the storm tracks for the last four decades.

We have computed correlation coefficients between March precipitation and the corresponding values of most standard teleconnection indices maintained by the U.S. Climate Prediction Center. Some marginally significant values were found with the raw (detrended) time series for the Scandinavian pattern 0.27 (0.28), the Pacific–North America pattern -0.36 (-0.32), and the Southern Oscillation index 0.33 (0.23). However, the role played by the NAO mode does seem to constitute the single most important large-scale factor to drive the entire changing behavior of storm track and precipitation over the large Euro–Atlantic area. It is known that this important large-scale circulation mode steers a large number of cyclones to Iberia (United Kingdom/Scandinavia) when its index is negative (positive). Therefore, it is only natural that the NAO index for the month of March presents a significant positive trend and that it is well correlated with the declining (increasing) frequency of wet WT's over Iberia (United Kingdom/Ireland). In fact, within the Iberian Peninsula, the region displaying the maximum correlation values between NAO and March precipitation is highly coincident with the region presenting the largest changes in precipitation. The spatially averaged series of precipitation shows a correlation value of -0.60 that decreases to -0.48 when computed with the detrended series. Nevertheless, it is not understood, as it is out of the scope of this paper, why the NAO index for March reveals such a consistent positive trend over the last four decades. It might be that this corresponds to a consistent climate change signal, possibly conditioned by the decreasing temperatures and geopotential height in the lower stratosphere (Baldwin and Dunkerton 2005), which are known to be influencing the signal of the tropospheric associated mode [Arctic Oscillation (AO) and NAO].

Finally, it should be emphasized that the region with significant March precipitation negative trend encloses the three major international Iberian river basins: Douro (North), Tagus (Center), and Guadiana (South) Rivers (Fig. 11a). Therefore, any significant change in precipitation will be reflected in relevant changes of other branches of the hydrological cycle, namely, river flow and subsurface water resources. That is the case of the Tagus gauge near the Portuguese–Spanish border (small black dot in Fig. 11b), which exhibits a very strong decline (significant at 1%) of river flow in March. Similar results were obtained for the Douro

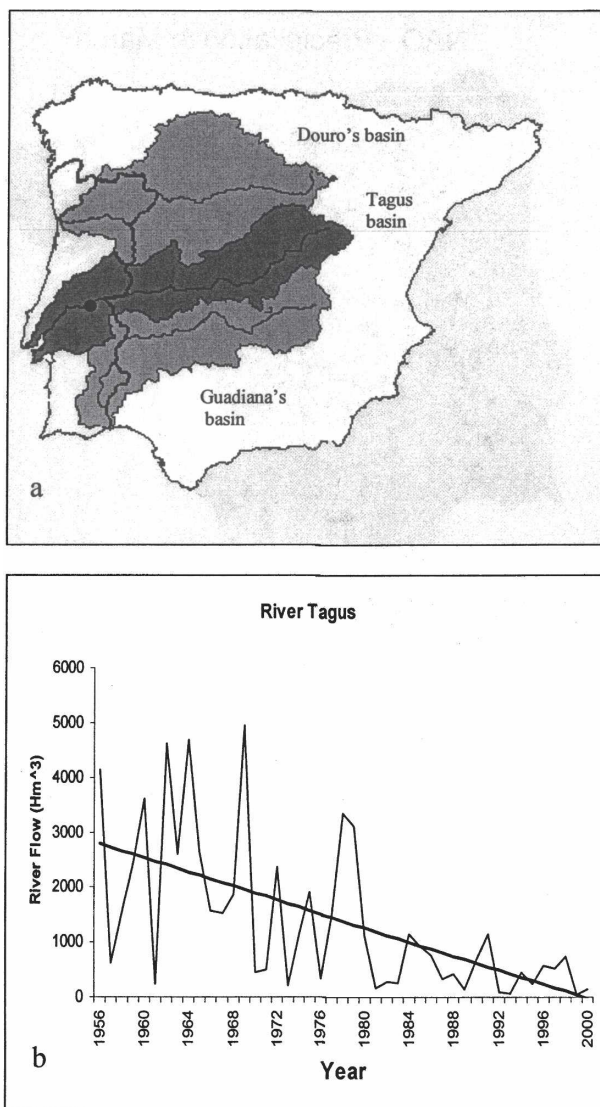


FIG. 11. (a) The three international river basins in Iberia (Douro, Tagus, and Guadiana) and (b) the interannual variability of March river flow for Tagus measured at Fratel's dam [black dot in (a)]. The corresponding linear regression trend is also represented.

River in the north and the Guadiana River in the south (not shown). Besides its use for agriculture and water supply to urban areas, these three rivers jointly account for circa 55% (70%) of Spanish (Portuguese) average total hydroelectric production (Trigo et al. 2004b). This fact highlights the relevance of such a strong decline in March precipitation, since the winter and springtime river flows account for the majority of runoff in these river basins (Trigo et al. 2004b). In the context of future scarce-precipitation scenarios over the Mediterranean Basin, such a dramatic decline is strong evidence of the

necessity to solve water resources management problems that have already arisen (Pereira et al. 2002).

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REFERENCES

- Alpert, P., and Coauthors, 2002: The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophys. Res. Lett.*, **29**, 1536, doi:10.1029/2001GL013554.
- Amanatidis, G. T., A. G. Paliatos, C. C. Repapis, and J. G. Bartzis, 1993: Decreasing precipitation trend in the Marathon area, Greece. *Int. J. Climatol.*, **13**, 191–201.
- Baldwin, M. P., and T. J. Dunkerton, 2005: The solar cycle and stratosphere–troposphere dynamical coupling. *J. Atmos. Sol.-Terr. Phys.*, **67**, 71–82.
- Barry, R. G., and R. J. Chorley, 1998: *Atmosphere, Weather and Climate*. Routledge, 409 pp.
- Blender, R. K., 1997: Identification of cyclone track regimes in the North Atlantic. *Quart. J. Roy. Meteor. Soc.*, **123**, 727–741.
- Corte-Real, J., B. Qian, and H. Xu, 1998: Regional climate change in Portugal: Precipitation variability associated with large-scale atmospheric circulation. *Int. J. Climatol.*, **18**, 619–635.
- Esteban-Parra, M. J., F. C. Rodrigo, and Y. Castro-Díez, 1998: Spatial and temporal patterns of precipitation in Spain for the period 1880–1992. *Int. J. Climatol.*, **18**, 1557–1574.
- García-Herrera, R., D. Gallego, E. Hernández, L. Gimeno, P. Ribera, and N. Calvo, 2003: Precipitation trends in the Canary Islands. *Int. J. Climatol.*, **23**, 235–241.
- , E. Hernández, D. Paredes, D. Barriopedro, J. F. Correoso, and L. Prieto, 2005: A MASCOTTE-based characterization of MCSs over Spain, 2000–2002. *Atmos. Res.*, **73**, 261–282.
- Goodess, C. M., and J. P. Palutikof, 1998: Development of daily rainfall scenarios for southeast Spain using a circulation-type approach to downscaling. *Int. J. Climatol.*, **18**, 1051–1083.
- , and P. D. Jones, 2002: Links between circulation and changes in the characteristics of Iberian rainfall. *Int. J. Climatol.*, **22**, 1593–1615.
- Hanssen-Bauer, I., and E. J. Forland, 1998: Long-term trends in precipitation and temperature in the Norwegian Arctic: Can they be explained by changes in atmospheric circulation patterns? *Climate Res.*, **10**, 143–153.
- HMSO, 1962: *Weather in the Mediterranean. I: General Meteorology*. 2d ed. Her Majesty's Stationery Office, 362 pp.
- Hoppe, H., and G. Kiely, 1999: Precipitation over Ireland—Observed change since 1940. *Phys. Chem. Earth*, **24**, 91–96.
- Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.
- Hurrell, J. W., 1995: Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. *Science*, **269**, 676–679.
- , 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophys. Res. Lett.*, **23**, 665–668.
- Jenkinson, A. F., and F. P. Collison, 1977: An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memo. 62, Met Office, London, United Kingdom, 18 pp.
- Jones, P. D., M. Hulme, and K. R. Briffa, 1993: A comparison of Lamb circulation types with an objective classification scheme. *Int. J. Climatol.*, **13**, 655–663.
- , T. Jonsson, and D. Wheeler, 1997: Extension to the North Atlantic Oscillation using instrumental pressure observations from Gibraltar and south-west Iceland. *Int. J. Climatol.*, **17**, 1433–1450.
- Karl, T. R., R. W. Knight, and N. Plummer, 1995: Trends in high-frequency climate variability in the twentieth century. *Nature*, **377**, 217–220.
- Kiely, G., J. D. Albertson, and M. Parlange, 1998: Recent trends in diurnal variation of precipitation at Valentia on the West coast of Ireland. *J. Hydrol.*, **207**, 270–279.
- Klein, A. M. G., and Coauthors, 2002: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *Int. J. Climatol.*, **22**, 1441–1453.
- Miranda, P., F. Coelho, A. Tomé, and A. Valente, 2002: 20th century Portuguese climate and climate scenarios. *Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures—SIAM*, F. D. Santos, K. Forbes, and R. Moita, Eds., Gradiva, 27–83.
- New, M. G., M. Hulme, and P. D. Jones, 1999: Representing twentieth-century space–time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. *J. Climate*, **12**, 829–856.
- Osborn, T. J., K. R. Briffa, S. F. B. Tett, P. D. Jones, and R. M. Trigo, 1999: Evaluation of the North Atlantic Oscillation as simulated by a climate model. *Climate Dyn.*, **15**, 685–702.
- Parry, M. L., 2000: *Assessment of Potential Effects and Adaptation for Climate Change in Europe: The ACACIA Project*. Jackson Environmental Institute, University of East Anglia, 320 pp.
- Pereira, J., and Coauthors, 2002: Forests and biodiversity. *Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures—SIAM*, F. D. Santos, K. Forbes, and R. Moita, Eds., Gradiva, 363–414.
- Piervitali, E., M. Colacino, and M. Conte, 1997: Signals of climatic change in the Central-Western Mediterranean Basin. *Theor. Appl. Climatol.*, **58**, 211–219.
- Pozo-Vázquez, D., M. J. Esteban-Parra, F. S. Rodrigo, and Y. Castro-Díez, 2001: A study on NAO variability and its possible non-linear influences on European surface temperatures. *Climate Dyn.*, **17**, 701–715.
- Qian, B., J. Corte-Real, and H. Xu, 2000: Is the North Atlantic

- Oscillation the most important atmospheric pattern for precipitation in Europe? *J. Geophys. Res.*, **105**, 11 901–11 910.
- Reale, O., L. Feudale, and B. Turato, 2001: Evaporative moisture sources during a sequence of flood in the Mediterranean region. *Geophys. Res. Lett.*, **28**, 2085–2088.
- Rodríguez-Puebla, C., A. H. Encinas, S. Nieto, and J. Garmendia, 1998: Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. *Int. J. Climatol.*, **18**, 299–316.
- Sáenz, J., J. Zubillaga, and C. Rodríguez-Puebla, 2001: Interannual variability of Winter precipitation in northern Iberian Peninsula. *Int. J. Climatol.*, **21**, 1503–1513.
- Schoenwiese, C. D., 1993: *Klimatrend-Atlas Europa 1891–1990 (Atlas of Climate Trends for Europe 1891–1990)*. Verlag, 218 pp.
- Serrano, A., V. L. Mateos, and J. A. García, 1999a: Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. *Phys. Chem. Earth*, **24**, 85–90.
- , A. J. Garcia, V. L. Mateos, M. L. Cancillo, and J. Garrido, 1999b: Monthly modes of variation of precipitation over the Iberian Peninsula. *J. Climate*, **12**, 2894–2919.
- Serreze, M. C., F. Carse, R. G. Barry, and J. C. Rogers, 1997: Icelandic low cyclone activity: Climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. *J. Climate*, **10**, 453–464.
- Simmons, A. J., 2001: Development of the ERA-40 data assimilation system. *Proc. Workshop on Reanalysis*, Reading, United Kingdom, ECMWF, 11–30.
- Smith, K., 1995: Precipitation over Scotland, 1757–1992: Some aspects of temporal variability. *Int. J. Climatol.*, **15**, 543–556.
- Spellman, G., 2000: The use of an index-based regression model for precipitation analysis on the Iberian Peninsula. *Theor. Appl. Climatol.*, **66**, 229–239.
- Thornes, J. B., 1998: Mediterranean desertification. *Atlas of Mediterranean Environments in Europe*, P. Mairota, J. B. Thornes, and N. Geeson, Eds., Wiley, 2–4.
- Tomás, C., F. Pablo, and F. L. Soriano, 2004: Circulation weather types and cloud to ground flash density over Iberian Peninsula. *Int. J. Climatol.*, **24**, 109–123.
- Trigo, I. F., 2005: Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: A comparison between ERA-40 and NCEP/NCAR reanalyses. *Climate Dyn.*, in press.
- , T. D. Davies, and G. R. Bigg, 1999: Objective climatology of cyclones in the Mediterranean region. *J. Climate*, **12**, 1685–1696.
- , —, and —, 2000: Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones. *Geophys. Res. Lett.*, **27**, 2913–2916.
- , G. R. Bigg, and T. D. Davies, 2002: Climatology of cyclogenesis mechanisms in the Mediterranean. *Mon. Wea. Rev.*, **130**, 549–569.
- Trigo, R. M., and C. C. DaCamara, 2000: Circulation weather types and their impact on the precipitation regime in Portugal. *Int. J. Climatol.*, **20**, 1559–1581.
- , and J. P. Palutikof, 2001: Precipitation scenarios over Iberia: A comparison between direct GCM output and different downscaling techniques. *J. Climate*, **14**, 4422–4446.
- , T. J. Osborn, and J. Corte-Real, 2002: The North Atlantic Oscillation influence on Europe: Climate impacts and associated physical mechanisms. *Climate Res.*, **20**, 9–17.
- , I. F. Trigo, C. C. DaCamara, and T. J. Osborn, 2004a: Climate impact of the European winter blocking episodes from the NCEP/NCAR reanalyses. *Climate Dyn.*, **23**, 17–28.
- , D. Pozo-Vázquez, T. J. Osborn, Y. Castro-Díez, S. Gámiz-Fortis, and M. J. Esteban-Parra, 2004b: North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *Int. J. Climatol.*, **24**, 925–944.
- Ulrich, U., and M. Christoph, 1999: A shift in the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas. *Climate Dyn.*, **15**, 551–559.
- Vlachos, E., and F. N. Correia, 1999: *Shared Water Systems and Transboundary Issues: With Special Emphasis on the Iberian Peninsula*. Luso-American Foundation, 454 pp.
- Xoplaki, E., F. J. Gonzalez-Rouco, J. Luterbacher, and H. Wanner, 2004: Wet season Mediterranean precipitation variability: Influence of large-scale dynamics. *Climate Dyn.*, **23**, 63–78.
- Zhang, X., X. L. Wang, and J. Corte-Real, 1997: On the relationships between daily circulation patterns and precipitation in Portugal. *J. Geophys. Res.*, **102**, 13 495–13 507.
- Zorita, E., V. Kharin, and H. von Storch, 1992: The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: Their interaction and relevance for Iberian precipitation. *J. Climate*, **5**, 1097–1108.